Science of the Total Environment 652 (2019) 289–299

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Understanding the impact of the changes in weather conditions on surface water quality

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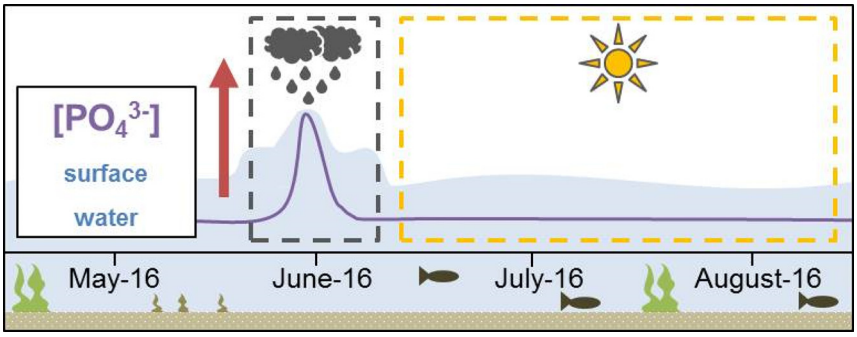
HIGHLIGHTS

- High-frequency monitoring is essential to understand the functioning of River Selle.
- The River Selle is dominated by groundwater inflows.
- The water quality degrades during storm events mainly due to phosphates.
- Climate change would degrade the overall water quality of River Selle.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 June 2018
Received in revised form 17 October 2018
Accepted 17 October 2018
Available online 18 October 2018

Editor: Damia Barcelo

Keywords:
High frequency monitoring
Principal component analysis
Hysteresis
River
Nutrient

ABSTRACT

The aim of this paper is to better understand the functioning of the River Selle (northern France) during dry weather and storm events, to assess the impact of a town on the surface water quality and to suggest qualitative assumptions on the vulnerability of water quality to weather conditions. Two high-frequency monitoring stations covering the Cateau-Cambrésis town were deployed during 4 months in 2016. River flow, water temperature, pH, dissolved oxygen, turbidity, conductivity, total organic carbon, nitrates and phosphates were monitored every 10 min. The water supply of the River Selle is mainly dominated by groundwater as shown by the behaviour of the river flow, the water temperature and the nitrate concentrations in both surface water and groundwater. The reference station located at the upstream of the river (Saint Souplet) exhibits low anthropogenic pressure during dry weather but is significantly impacted during storm events. At the downstream of the Cateau-Cambrésis town, the water quality is severely impacted by phosphates during dry weather mainly due to wastewater inputs into the river. An additional load of pollution is highlighted during storm events. According to our results, the water quality of the River Selle would degrade if actions to reduce dry-weather and storm events pollution sources are not undertaken rapidly. Moreover, nutrients, particularly phosphates, are clearly in excess in this system. Efforts to combat soil leaching and the revision of sewage systems and urban wastewater treatment in the catchment are two key points to tackle. Finally, this study shows the importance of understanding the current behaviour of a given river towards dry weather and storm events before suggesting local scenarios of the impact of climate change on surface water quality.

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https://doi.org/10.1016/j.scitotenv.2018.10.246
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1. Introduction

According to the observations of increased global average air and ocean temperatures, snow melting and sea level rise (Bates et al., 2008), global warming is undoubtedly occurring (IPCC, 2014, 2007). The consequences of climate change on continental water availability and quality are of growing concern and the vulnerability of water bodies to climate change may be exacerbated by multiple pressures such as population growth, environmental pollution and land-use changes (Kundzewicz, 2008). However, the impact of climate change on surface water quality at regional scales is not clearly established (Whitehead et al., 2009).

In 2012, the Explore 2070 project conducted by the French Ministry of the Environment developed climatic models to assess the impact of climate change on aquatic environments and water resources in different regions of France by the end of the year 2070. The project also aimed to develop and evaluate adaptation strategies at regional scales (Carroget et al., 2017). Seven atmospheric and two hydrological models were used and compared upon the IPCC's Representative Concentration Pathway (RCP) 6.0 scenario which represents the intermediate scenario where no additional efforts to limit gas emissions are made (IPCC, 2014). Results from the Explore 2070 project were limited to hydro (geo)logical data only and did not give predictions on the evolution of surface water quality. Despite the significant uncertainties of the Explore 2070 models, the latter provided suitable information for the assessment of climate change impacts. In the Artois-Picardy basin (northern France), a clear trend seemed to be emerging. An increase in the average air and water temperatures (by 2.0 °C and 1.6 °C respectively) leading to a decrease in the groundwater recharge (by 6–46%) and river flow (by 25–40%) are expected by the end of the year 2070 (CBAP, 2016). These changes may have significant negative impacts on surface water quality as previously mentioned by Whitehead et al. (2009) who conducted a study on the potential impacts of climate change on surface water quality in UK.

Long-term monitoring of environmental variables can be used to build climate impact models (Hewitson et al., 2014). In northern France, catchment monitoring programmes run by the Regional Direction of the Environment, Landscaping and Housing (DREAL) and the Artois-Picardy Water Agency (APWA), have been providing historical water quantity and quality data since the '70s. However, long-term trends are largely influenced by non-climate related factors such as urbanisation, agricultural practices or construction of wastewater treatment facilities (Bates et al., 2008). Moreover, the historical data available for northern France are not always adequate for impact predictions for the following reasons: (i) the lack of uniformity in the measurement methods contributes to difficulty in building a robust database. For example, before 2008, metals were quantified on raw water whereas now they are measured on filtrated water; (ii) the monitoring programmes are based on a low-frequency sampling regime (weekly or monthly). Although low-frequency monitoring can help in analysing long-term trends (Kirchner et al., 2004), they can obscure complex hydrochemical patterns (Halliday et al., 2012), especially during storm events when the hydrological response of catchments may vary from minutes to hours (Horsburgh et al., 2010). Besides, studies based on high-frequency monitoring have shown that water quality parameters have wide spatial-temporal variations (Halliday et al., 2012; Ivanovsky et al., 2016; Kirchner et al., 2004; Neal et al., 2012; Nimick et al., 2003; Superville et al., 2018; Wade et al., 2012). Conducting long-term high-frequency monitoring studies can therefore help to better understand the processes linked to the catchment hydrology and hydrochemistry (Halliday et al., 2012) such as storm-event and nutrient dynamics (Bowes et al., 2015; Halliday et al., 2014; Wade et al., 2012).

The scope of this paper is to examine the evolution of the surface water quality of the River Selle (northern France). River flow, water temperature, dissolved oxygen, pH, turbidity, conductivity, total organic carbon, phosphates and nitrates were monitored on a high-frequency basis every 10 min during 4 months (May–August 2016). The study focuses on the variations of the measured parameters during dry-weather and storm events. This paper also tackles the impact of the Cateau-Cambrésis town (around 7000 inhabitants) on the surface water quality of the River Selle through the deployment of 2 high-frequency monitoring stations at the upstream and downstream of the town. To support and strengthen our interpretations, multivariate data analysis was performed to highlight correlations and trends that could hardly be detected by expert eyes. Finally, qualitative forecasts of the impact of climate change on the surface water quality of the River Selle were given according to the general trends predicted by the Explore 2070 models for the Artois-Picardy basin.

2. Material and methods

2.1. Study area

The River Selle is a 46-km long river within the Artois-Picardy basin in northern France (Fig. 1). The main source of the river is located 120 m above sea level at Molain. After crossing several towns, namely Saint Souplet, Cateau-Cambrésis, Neuvilly and Solesmes, the River Selle enters the River Scheldt at Douchy-les-Mines. The flow at the convergence of the river is on average 2.5 $m^3 s^{-1}$. According to the flow data provided by the DREAL from 1983 to 2016 (see Supporting Information), the high flow generally starts from January to June (average value of 2.7 $m^3 s^{-1}$) and the low flow starts from July to December (average value of 2.3 $m^3 s^{-1}$). During our study in 2016, the difference between the high flow (average value of 2.5 $m^3 s^{-1}$) and the low flow (average value of 2.4 $m^3 s^{-1}$) was not significant.

The River Selle has three main but small tributaries: Essarts, Richemont, and Béart brooks representing <20% of the total river flow. The catchment of the River Selle drains an area of 252 km^2 and receives an annual rainfall of 735 mm. The catchment geology is predominantly Seno-Turonian chalk (DDTM, 2016). The land-use of the catchment is distributed as follows: 69% of cultivated agricultural land (mostly wheat, maize and barley), 15% of grassland and pasture land, 11% of urban and industrial zones scattered along the river and 5% of forested areas concentrated at the upstream of the river. The groundwater quality in the catchment is mostly affected by diffuse agricultural pollution [nitrates, persistent pesticides such as atrazine and its degradation products (desethylatrazine and desisopropylatrazine)]. Metal pollution is very low according to the APWA's previous monitoring campaigns (http://www.eau-artois-picardie.fr/). Around 40,000 inhabitants within the catchment are connected to four main wastewater treatment plants (WWTPs). The largest WWTP (22,000 population equivalent) is located at Cateau-Cambrésis in between Saint Souplet and Neuvilly (Fig. 1).

2.2. High-frequency monitoring

Two automatic mobile monitoring stations belonging to the APWA were used to provide on-line measurements of water quality parameters (river flow, water temperature, pH, dissolved oxygen, turbidity, conductivity and total organic carbon) and nutrients (nitrates and phosphates). Station 1 was deployed at Saint Souplet (4 km away from the main source) where the surface water quality is supposedly undisturbed by anthropogenic pressures. Station 2 was deployed 17 km away from the main source at Neuvilly (Fig. 1) for the assessment of the impact of a 7000 inhabitant-town on the water quality of the river. Data of the 9 parameters were collected every 10 min from May to August 2016 in the spring and summer seasons. The 10-min interval corresponds to the highest frequency of the monitoring stations. This frequency of measurement was chosen in order to clearly identify short-term variations such as daily cycles, short storm events and pollution discharges. Besides, to strengthen our statistical data treatment and the study of hysteresis patterns, a large dataset had to be collected.

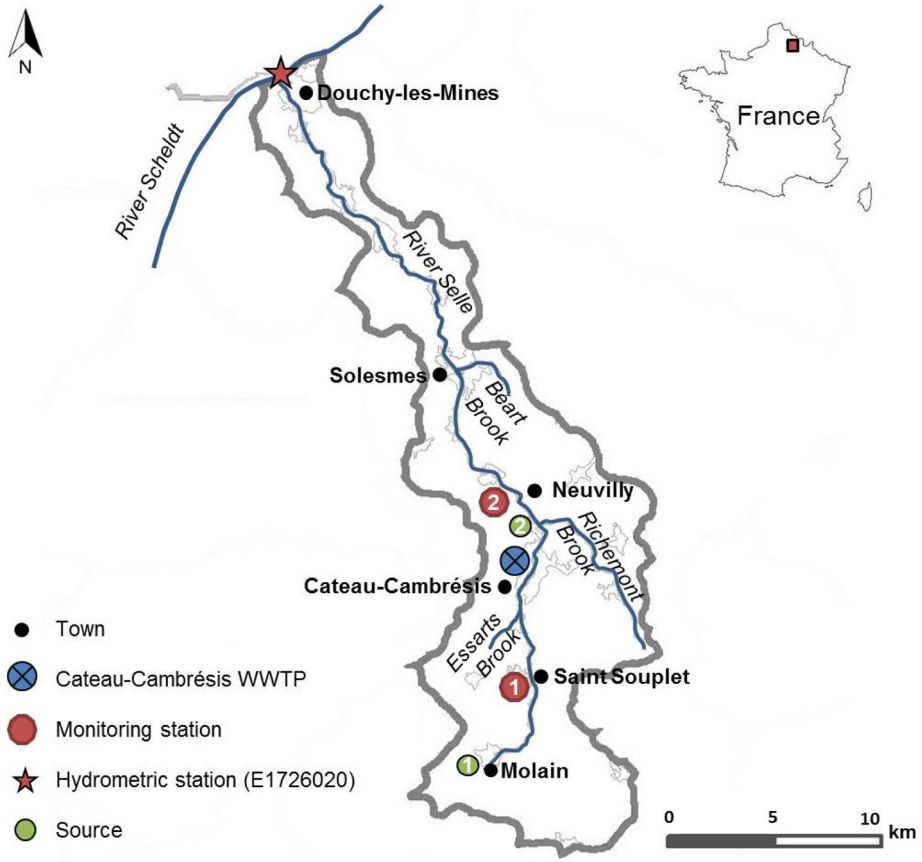

Fig. 1. Map of the River Selle catchment (northern France) showing the main towns (black circles), the Cateau-Cambrésis wastewater treatment plant (blue circle), the 2 high-frequency monitoring stations (red circles), the 2 main identified sources (green dots) and the hydrometric station (red star) at the downstream of the river.

Unfortunately, such monitoring campaign could not be performed during the winter season due to technical and financial issues.

A full description of the measurement methods can be found in Ivanovsky et al. (2016). Briefly, the monitoring stations were supplied with surface water by a submerged pump (15 $m^3\ h^{-1}$). River flow velocity was recorded by a Doppler sensor. Probes were used to measure water temperature, pH, conductivity, dissolved oxygen and turbidity. Total organic carbon (TOC) and phosphates were measured by infrared spectroscopy and spectrophotometry respectively whereas nitrates were quantified by UV molecular absorption spectroscopy. Intercalibration of the stations was performed as follows: one discrete water sample from each monitoring station was collected once a week during the 4 months of monitoring and sent to an accredited laboratory for the measurements of TOC, pH, conductivity, nitrates and phosphates. The difference between the monitoring stations and laboratory measurements was generally <10%.

2.3. Data analysis

2.3.1. Determination of storm events, hysteresis indexes and trajectories

Storm events were determined from the hydrographs of the monitoring stations. Increases in river flow exceeding the base flow by 20% were defined as storm events (Blaen et al., 2017). The base flow was calculated by averaging dry-weather flows. A classification of the storm events was established according to their intensity: 'small', 'average' or 'heavy'. A 'small' storm event was defined by an increase of 20–50% above the base flow. An increase of 50–100% accounted for an 'average' storm event and finally flows exceeding the base flow by 100% defined 'heavy' storm events.

To investigate for hysteresis patterns among all the monitored parameters, concentration-flow curves were plotted for each storm event. The concentration and flow values were normalised according to the equation given by Lloyd et al. (2016) (Eqs. (1) and (2), respectively):

$$\text{Normalised Qi} = \frac{\text{Qi} - \text{Qmax}}{\text{Qmax} - \text{Qmin}} \quad (1)$$

$$\text{Normalised Ci} = \frac{\text{Ci} - \text{Cmax}}{\text{Cmax} - \text{Cmin}} \quad (2)$$

Q_i and C_i refer respectively to the flow and concentration at time step i. Q_{max} and Q_{min} are respectively the maximum and minimum flows during an individual storm event. The maximum and minimum concentrations during an individual storm event are defined respectively by C_{max} and C_{min}.

Clockwise hysteresis loops often occur when concentrations are higher on the rising limb of the hydrograph. On the other hand, anti-clockwise loops often occur when concentrations on the falling limb are higher (Bowes et al., 2015). Hysteresis trajectories (clockwise, anti-clockwise, complex or no hysteresis) were determined by the calculation of hysteresis indexes (HI_{mid}) according to the method developed by Lawler et al. (2006). The method involves two steps: (i) the determination of the mid-point discharge (Q_{mid}) for each storm event which in our case is equal to 0.5; and (ii) the interpolation of the concentration values at Q_{mid} on the rising and falling limbs of the hydrograph. Major hysteresis loops are characterised by high values of HI_{mid}. Positive HI_{mid} values describe clockwise hystereses while negative HI_{mid} values describe anti-clockwise hystereses. When no hysteresis is present, *i.e.*

when the concentrations on the rising and falling limbs are equal, the HI_{mid} assumes a zero value.

2.3.2. Principal component analysis

Principal component analysis (PCA) is a bilinear model based on the construction of common factors which are linear combinations of the original variables (Bro and Smilde, 2014). These factors are called principal components (PCs) and aim at extracting hidden structures from the original data. PCs account for the direction of maximum variance under the constraint of orthonormality. PCA allows the simultaneous analysis of a large number of samples characterised by multiple variables. In the present study, the PCA models were built using Matlab R2012b (The MathWorks, Inc.) and the Eigenvector PLS toolbox (Eigenvector Research, Inc.). The data matrices consisted of 5778 rows, resp. 6789 rows, corresponding to the samples collected during the monitoring period and 9 columns corresponding to the measured variables (river flow, water temperature, pH, dissolved oxygen, turbidity, conductivity, TOC, nitrates and phosphates) for Station 1, resp. Station 2. Measurement breakdowns corresponding to unusable data were discarded so that no missing data are present in the data matrices. Autoscaling (mean centering and scaling each variable to unit standard deviation) was finally applied to the data before building individual PCA models for Station 1 and 2.

2.4. Data provided by external institutions

Historical flow data from 1983 to 2016 were collected from the HYDRO website (MEDDE, 2015). Note that the hydrometric station E1726020 is located at the convergence of the River Selle and River Scheldt at Douchy-les-Mines (Fig. 1). Three groundwater samples from Source 1 and two groundwater samples from Source 2 were collected and measured by the APWA during the high-frequency monitoring campaign. The groundwater measurements are given in Table 1. Rainfall data were also provided by the APWA and were included in the results section (Fig. 2a).

3. Results

3.1. Data related to dry weather

3.1.1. River flow

An average dry-weather flow of 0.50 $m^3\ s^{-1}$ was measured from May to August 2016 at Saint Souplet (Station 1). At the downstream of Cateau-Cambrésis (Station 2), a higher average dry-weather flow of 1.36 $m^3\ s^{-1}$ was recorded. The low standard deviation values ($\pm$ 0.01 $m^3\ s^{-1}$ and $\pm$ 0.06 $m^3\ s^{-1}$ resp. for Station 1 and Station 2) indicate that the river flow was constant during the dry days (Fig. 2b and Table 2).

Table 1
Physico-chemical parameters measured by the Artois-Picardy Water Agency from May to August 2016 at Source 1 (Molain) and Source 2 (Neuvilly).

	Source 1			Source 2		
	Min	Average	Max	Min	Average	Max
Water temperature (°C)	11.1	11.4	11.8	11.4	11.7	11.9
Dissolved oxygen ($mgO_2\ L^{-1}$)	6.5	7.8	8.5	7.5	8.3	9.1
pH (u.pH)	7.2	7.2	7.3	7.2	7.3	7.4
Conductivity ($\mu S\ cm^{-1}$)	619	662	684	700	740	779
Turbidity (NFU)	0.4	1.0	2.3	0.3	0.5	0.7
DOC ($mg\ L^{-1}$)	0.8	0.8	0.9	0.6	0.7	0.8
Phosphates ($mgPO_4^{3-}\ L^{-1}$)	0.18	0.20	0.22	0.18	0.19	0.19
Nitrates ($mgNO_3^-\ L^{-1}$)	32.0	34.0	35.0	48.0	48.5	49.0

Abbreviations: Min: Minimum value; Max: Maximum value; DOC: Dissolved Organic Carbon.

3.1.2. Water temperature, dissolved oxygen, pH and conductivity

Water temperature, dissolved oxygen and pH exhibited diurnal variations throughout the high-frequency monitoring period (Fig. 2c,d,e). During the dry days, the water temperature values at Stations 1 and 2 were on average 11.7 °C and 13.6 °C respectively. At both stations, the lowest water temperature values were measured at night. Higher amplitudes of the daily cycles were observed at Station 2. Dissolved oxygen and pH also displayed higher values during the day than at night and the average dissolved oxygen level and pH were slightly higher at Station 2 (Table 2). As for conductivity, the average values recorded at both stations were almost similar. However, the maximal conductivity values at Station 2 were higher than those at Station 1 (Table 2). Finally, the minimal values of conductivity measured during the day highlighted diurnal variations of conductivity.

3.1.3. Turbidity, TOC, nitrates and phosphates

Turbidity seemed to follow the same trend as conductivity (Fig. 2g) with the highest values recorded at night. A difference of 27 NFU in the average values was measured between the two monitoring stations, with greater values at the downstream of Cateau-Cambrésis (Table 2). As for TOC, no particular trend was observed and no dry-weather peaks were identified at both monitoring stations (Fig. 2h). However, the average TOC values at the downstream of Cateau-Cambrésis were significantly higher (Table 2). Finally, during the dry-weather period, both nitrate and phosphate concentrations increased from the upstream of the river to the downstream (Table 2). No phosphate peak was identified at Station 1 during dry weather.

3.2. Data related to storm events

3.2.1. River flow

According to the definition of a storm event (Subsection 2.3.1), 5 and 7 storm events were identified at Station 1 and 2 respectively, from May to August 2016 (Fig. 2b). Higher average flow values were recorded at the downstream of Cateau-Cambrésis by a factor of 3 (Table 2).

3.2.2. Water temperature, dissolved oxygen, pH and conductivity

At both monitoring stations, the water temperature during the storm events was higher than during dry weather. On the contrary, dissolved oxygen, pH and conductivity values decreased during the storm events (Fig. 2c,d,e and Table 2).

3.2.3. Turbidity and TOC, nitrates and phosphates

Both turbidity and TOC values increased during the storm events. At the downstream of Cateau-Cambrésis, higher values were recorded during the storm events but the difference between the dry weather and storm event values was similar to Station 1 (Table 2). The variations in turbidity and TOC during storm events at both stations were characterised by sharp increases followed by steady drops within few hours (Fig. 2g,h). Phosphates followed the same trend as turbidity and TOC, with an increase in concentration during storm events at both stations. On the other hand, nitrates decreased during the storm events at both stations. These variations were clearly visible on the 23rd of June 2016 (Fig. 2i,j). During this storm event, the phosphate concentrations at Station 2 reached the saturation value of the instrument (5 $mgPO_4^{3-}\ L^{-1}$).

3.3. Nitrate and conductivity hystereses

5 and 7 storm events were identified at Station 1 and 2 respectively (Fig. 3). Given the classification described in Section 2.3.1, 3 'small', 1 'average' and 1 'heavy' storm event were identified at Station 1, while 4 'small', 2 'average' and 1 'heavy' storm event were identified at Station 2 (Table 3). Among all the parameters measured, only the nitrates and conductivity exhibited clear hysteresis patterns. Turbidity and phosphates seemed to display hysteresis patterns but the hystereses were

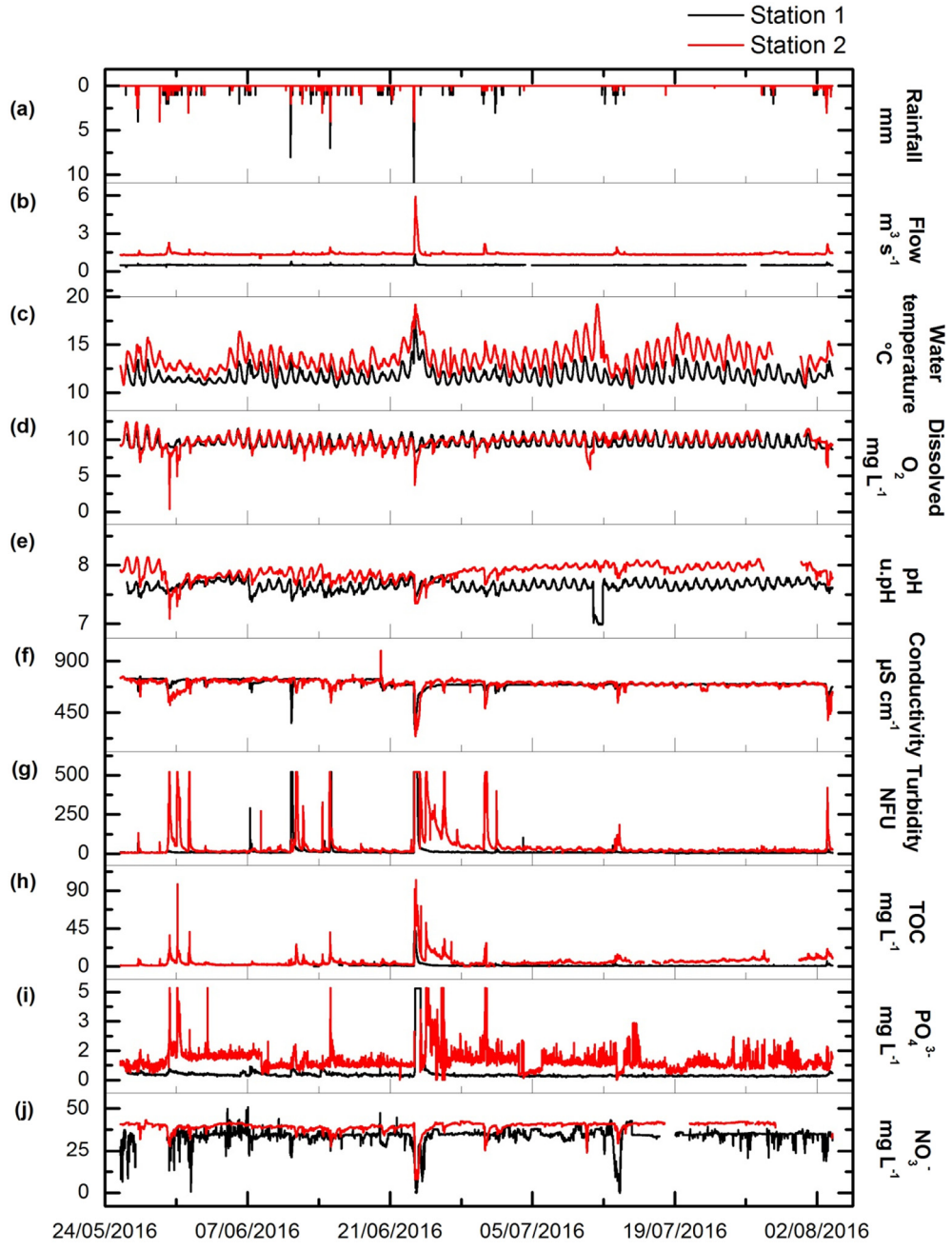

Fig. 2. Time series plots of the different parameters measured during the high-frequency monitoring at Station 1 (black line) and Station 2 (red line): a) rainfall; b) river flow; c) water temperature; d) dissolved oxygen (O_2); e) pH; f) conductivity; g) turbidity; h) total organic carbon (TOC); i) phosphates (PO_4^{3-}); j) nitrates (NO_3^-).

very complex. Hysteresis indexes (HI_{mid}) were therefore calculated for nitrates and conductivity only.

The hysteresis trajectories for nitrates and conductivity were clearly clockwise since all the HI_{mid} values calculated were positive (Table 3). The values also increased correspondingly to the classification of the different storm events. For the 'small' storm events at both monitoring stations, the HI_{mid} values of nitrates and conductivity varied between 0.2 and 4.7. The nitrate concentration-flow curves for the 'small' storm events were characterised by a constant value and a sudden decrease before returning to its initial concentration. The same phenomenon was observed for conductivity. Due to instrumental problems, no conductivity data were collected at Station 1 during the storm event 5. The 'average' storm events involved the event 4 at Station 1 and 2 and the event 7 at Station 2. The HI_{mid} values of nitrates and conductivity for the 'average' storm events ranged between 1.2 and 20.3. The only 'heavy' storm event (storm event 6 at both stations) occurred on the 23rd of June 2016 where the river flow increased up to 6.0 $m^3\ s^{-1}$. The hysteresis patterns at Station 1 were too complex for hysteresis index calculations. At Station 2, a HI_{mid} of 724 and 1.9 were calculated for nitrates and conductivity respectively (Table 3). During both 'average' and 'heavy' storm events, the concentration-flow curves produced hysteresis loops with a negative gradient.

3.4. Exploring the data structure

Principal component analysis is a fundamental tool to investigate the structure of multivariate data, *i.e.* datasets containing multiple rows and columns. By reducing the dimensionality of the high-frequency dataset while preserving as much variability as possible, interpretability of the data structure was increased. 95% of the total variance in the dataset

Table 2
Summary of the high-frequency data collected from May to August 2016 at Station 1 and 2 during dry weather and storm events. Several values were coloured according to the threshold values assigned by the Water Framework Directive for the water quality status (see Supporting Information). Blue: high; green: good; yellow: moderate; orange: poor; and red: bad.

	Station 1								Station 2							
	Dry weather				Storm events				Dry weather				Storm events			
	Min	Average	Max	SD	Min	Average	Max	SD	Min	Average	Max	SD	Min	Average	Max	SD
Flow ($m^3 s^{-1}$)	0.37	0.50	0.73	0.01	0.49	0.57	1.34	0.15	1.05	1.36	2.16	0.06	1.28	1.70	5.90	0.72
Water temperature (°C)	10.5	11.7	14.3	0.7	10.8	13.0	18.4	1.6	10.8	13.6	19.2	1.2	11.6	13.8	19.2	1.9
Dissolved oxygen ($mgO_2 L^{-1}$)	8.7	9.6	11.5	0.7	8,2	9.2	11.0	0.7	5.9	9.8	12.4	0.8	0.4	8.9	11.1	1.3
pH (u·pH)	7.0	7.7	7.9	0.1	7.4	7.6	7.8	0.1	7.4	7.9	8.1	0.1	7.1	7.7	8.1	0.2
Conductivity ($\mu S\ cm^{-1}$)	539	707	752	24	268	611	767	113	385	709	990	30	245	625	748	105
Turbidity (NFU)	3	9	83	7	5	143	>520	201	3	36	>520	58	6	170	>520	183
TOC ($mg L^{-1}$)	0.1	0.9	6.4	0.4	0.8	9.2	42.2	12.6	<0.1	5.1	51.8	4.1	0.1	13.2	102.8	17.5
Phosphates ($mgPO_4^{3-} L^{-1}$)	0.16	0.28	1.32	0.08	0.18	1.34	4.99	1.83	0.01	1.03	4.99	0.49	0.01	1.49	>5	1.04
Nitrates ($mgNO_3^- L^{-1}$)	<1	34.2	50.7	3.8	<1	25.9	35.9	9.5	23.7	40.0	43.2	1.6	8.1	33.8	41.5	7.7

Abbreviations: Min: Minimum value; Max: Maximum value; SD: Standard deviation; TOC: Total organic carbon.

was explained by 6 principal components (PCs) for Station 1 and 7 for Station 2. However, in both cases, only the first 2 PCs were comprehensively interpreted since they explained most of the variations in the data.

3.4.1. Station 1

The first 2 PCs accounted for 51% (PC 1) and 22% (PC 2) of the total variance in the dataset. The scores plot of PC 1 points out that most of the samples remained in the 95% confidence limit, except for some extreme samples (samples 1039 to 1151) (Fig. 4a). The loading plot of PC 1 shows that the variables TOC, phosphates, water temperature, turbidity and flow were anti-correlated to nitrates, conductivity, dissolved oxygen and pH (Fig. 4b). The scores plot of PC 2 shows that 22% of the total variation in the dataset was explained by cyclic patterns (Fig. 4c). The variables nitrates, dissolved oxygen, pH and water temperature were anti-correlated to phosphates, conductivity and turbidity, as indicated on the loading plot of PC 2. Flow and TOC remained unchanged (Fig. 4d).

3.4.2. Station 2

The percentage variance explained by PC 1 and PC 2 were 43% and 15% respectively. The scores plot of PC 1 shows more extreme samples compared to that of Station 1 (Fig. 4e). The loading plot of PC 1 points out that the correlation between the variables was similar to that of Station 1, except for water temperature which remained unchanged (Fig. 4f). The cyclic patterns in the scores plot of PC 2 are less regular than that of Station 1 (Fig. 4g). The loading plot of PC 2 shows that

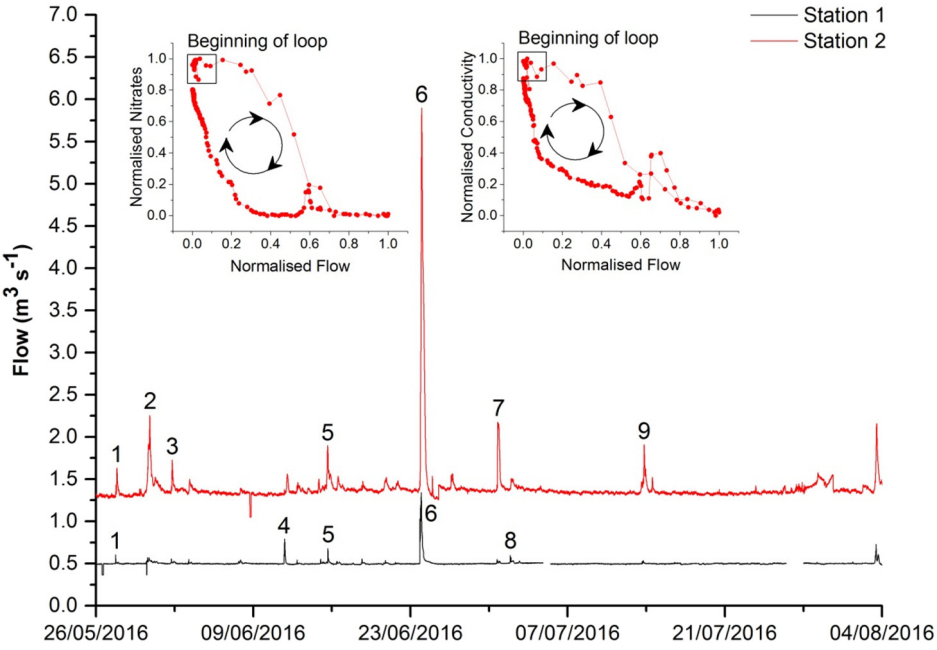

Fig. 3. River flow at Station 1 (black line) and Station 2 (red line) throughout the high-frequency monitoring programme. Each storm event is numbered in ascending order according to the date of the storm event. The 2 insets display the major clockwise hysteresis loops of nitrate (to the left) and conductivity (to the right) during the storm event 6 at Station 2.

Table 3
Summary of the hysteresis indexes (HI_{mid}) and trajectories for nitrates and conductivity observed in the River Selle between May and August 2016.

	Storm event	Classification of the storm event	Nitrates		Conductivity	
			HI_{mid}	Trajectory	HI_{mid}	Trajectory
Station 1	1	Small	No data		3.1	Clockwise
	4	Average	20.3	Clockwise	7	Clockwise
	5	Small	6.0	Clockwise	No data	
	6	Heavy	Complex pattern		Complex pattern	
	8	Small	Complex pattern		Complex pattern	
Station 2	1	Small	0.3	Clockwise	0.2	Clockwise
	2	Average	3.2	Clockwise	5.4	Clockwise
	3	Small	Complex pattern		Complex pattern	
	5	Small	1.2	Clockwise	1.6	Clockwise
	6	Heavy	724	Clockwise	1.9	Clockwise
	7	Average	1.2	Clockwise	1.7	Clockwise
	9	Small	4.7	Clockwise	4.4	Clockwise

conductivity was anti-correlated to all the other variables during the high-frequency monitoring (Fig. 4h).

4. Discussion

Before suggesting local scenarios of the impact of climate change on the River Selle, it is important to understand its functioning. Results from this high-frequency monitoring study including the variations in river flow, nitrate concentrations and water temperature indicate that the River Selle is mainly fed by groundwater. The assessment of the historical flow data (1983 to 2016) points out a difference of only 0.4 $m^3 s^{-1}$ between the high and low flows. This means that the average river flow is relatively constant throughout the year. However, since Pickaert and Quide (2011) clearly linked the flow of the River Selle to the height of the piezometric level, the gradual drop in the groundwater recharge as predicted by the Explore 2070 models, would impact the overlying flow of the river over the next decades. The dilution of the nitrates during storm events and the average dry-weather nitrate concentrations at both monitoring stations being relatively similar to the concentrations measured in the groundwater [34.2 $mgNO_3^- L^{-1}$ at Station 1 and 34.0 $mgNO_3^- L^{-1}$ at Source 1; 40.0 $mgNO_3^- L^{-1}$ at Station 2 and 48.5 $mgNO_3^- L^{-1}$ at Source 2 (Table 1)] are clear evidence that exchanges with the groundwater are predominant in the River Selle. Jarvie et al. (2005) also reported similar nitrate concentrations in the surface water and groundwater in the Hampshire Avon catchment which is groundwater-dominated. Another characteristic of rivers dominated by groundwater is a stable thermal regime (Sear et al., 1999). Ivanovsky et al. (2016) studied the fluctuations in the water temperature of the River Marque (northern France) which is primarily fed by storm run-offs. They reported that the thermal variations in the River Selle were 40% lower than that in the River Marque. This implies that River Selle has a more stable thermal regime than a river fed by run-offs. Given the fact that the River Selle is dominated by groundwater, the decrease in groundwater recharge (6–46%) as predicted by the Explore 2070 project, will most likely impact the water demand in the catchment and decrease the flow of the River Selle. The latter would become inadequate to maintain ecological functions such as in-stream habitats for fish and other aquatic species (Taylor et al., 2013). Furthermore, due to the reduction in flushing rates during extreme low flows, the retention and concentration of pollutants would increase (Mosley, 2015). According to the predictions for northern France, the dilution of pollution would decrease severely with the decrease in river flow (APWA, 2008). However, political, social and technological aspects such as: (i) the evolution of the population which is currently dropping in the River Selle catchment; (ii) the evolution of water demand; (iii) the implementation of new wastewater treatment technologies; and (iv) political choices regarding environmental protection, thereby revising the sewer systems in the catchment, can help to mitigate these predictions (Capon et al., 2018).

The strategic positioning of the 2 monitoring stations covering the Cateau-Cambrésis town provided interesting insights on the impact of one-off climatic events on the water quality of the River Selle. Station 1, which was located in a rural area (Saint Souplet), was considered as our reference station. This assumption was confirmed by the PCA models. Given the results of the scores and loading plots of PC 2, the daily variations of photosynthesis and respiration in the river can be explained by PC 2. Indeed, biogeochemical processes involving increases in dissolved oxygen, pH and water temperature during the day and decreases at night are now well established (Nimick et al., 2011). The highly significant positive loadings of dissolved oxygen, pH and water temperature together with the regular cyclic dispersion of the scores values in PC 2 (Fig. 4c,d) indicate that the water quality of the River Selle at Saint Souplet is mostly governed by biological activities during dry weather. Anthropogenic pressures can therefore be neglected at the upstream of the river. Moreover, the dry-weather dissolved oxygen level during the high-frequency monitoring at Saint Souplet (9.6 $mgO_2 L^{-1}$) was on average good and the average pH value (7.7 u·pH) suitable for aquatic life (Boyd, 2015). Although the PCA models highlighted the photosynthesis/respiration processes, they did not bring to light the diurnal variations of conductivity and turbidity. Night-time increases of conductivity are reported to be linked to the diurnal changes in photosynthesis/respiration, more precisely to the increase of bicarbonate (HCO_3^-) concentrations derived from respired CO_2 (Halliday et al., 2014; Hayashi et al., 2012). On the other hand, nocturnal feeding and movement of fish and invertebrates can be responsible for night-time increases of turbidity (Loperfido et al., 2010; Nimick et al., 2011). The conductivity and turbidity cycles being less frequent than those of dissolved oxygen, pH and water temperature throughout the high-frequency monitoring could explain why the PCA models did not reveal the diurnal variations of conductivity and turbidity.

The comparison of the average dry-weather values (Table 2) and the scores and loading plots of PC 2 between the 2 monitoring stations highlight the impact of the Cateau-Cambrésis town on the water quality of the River Selle. The disturbances in the score values at Station 2 together with the positive correlation between the loadings of oxygen, pH, water temperature and TOC, phosphates, nitrates, turbidity (Fig. 4g,h) point out that during dry weather the water quality at the downstream of Cateau-Cambrésis is governed by photosynthesis/respiration processes and to a lesser extent urban inputs. Alternating period of precipitation/dissolution mainly controlled by pH and dissolved oxygen fluctuations can describe the negative correlation of conductivity in PC 2 with oxygen and pH (Hayashi et al., 2012). The urban area around Cateau-Cambrésis and the Cateau-Cambrésis WWTP undeniably contribute to the observed increases in the loading values of all the variables in PC 2. These increases can be attributed mostly to WWTP discharges during dry weather but also to other sources such as illicit discharge connections, leaking sewer systems, and failing septic systems (Paul and Meyer, 2001). The reduction in the river flow as predicted by the Explore 2070 project, will limit the dilution of pollutants coming mainly from WWTPs (phosphates in our case, pharmaceutical residues and metals such as Cu and Zn) or from soil leaching, especially during storm events. If wastewater treatment efficiency is not improved, the physico-chemical and ecological quality status of the river will degrade severely.

According to the Water Framework Directive (WFD), the assessment of the ecological quality status (EcoQS) of a river is based upon biological, hydromorphological and physico-chemical quality elements. The EcoQS is defined by 5 classes: 'bad', 'poor', 'moderate', 'good' and 'high' (EU, 2000) (see Supporting Information). In our case, the physico-chemical parameters measured during the high-frequency monitoring, namely, dissolved oxygen, pH, TOC, nitrates and phosphates, were considered for the evaluation of the physico-chemical status (PCQS) of the River Selle. A qualitative assessment using the high-frequency data

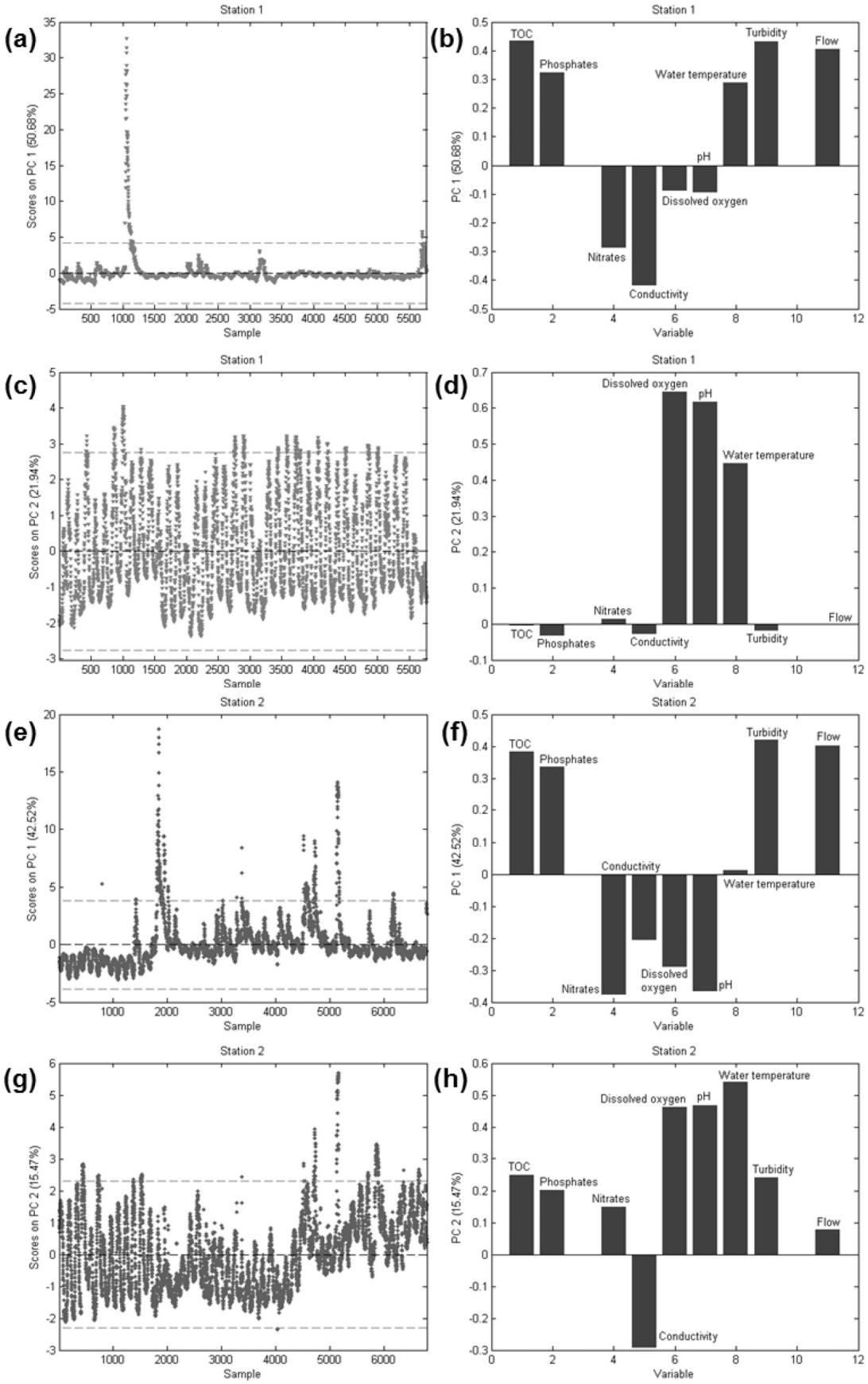

Fig. 4. The scores and loading plots of the PCA models built using the high-frequency monitoring dataset of Station 1 and 2: a) scores plot of PC1 for Station 1; b) loading plot of PC1 for Station 1; c) scores plot of PC2 for Station 1; d) loading plot of PC2 for Station 1; e) scores plot of PC1 for Station 2; f) loading plot of PC1 for Station 2; g) scores plot of PC2 for Station 2; h) loading plot of PC2 for Station 2.

shows that at present, the overall dry-weather PCQS at Saint Souplet is 'good' whereas at the downstream of Cateau-Cambrésis, the overall PCQS is 'moderate'. Based on the average dry-weather values dissolved oxygen and pH values obtained during the high-frequency monitoring, the PCQS at both Saint Souplet and at the downstream of Cateau-Cambrésis is evaluated as 'high' since the average values exceed the threshold concentration of 8.0 $mgO_2\ L^{-1}$ and range between 6.5 u·pH and 8.2 u·pH. The nitrate concentrations (<50.0 $mgNO_3^-\ L^{-1}$) also contribute the 'good' PCQS at both monitoring station. Considering the TOC (>5.0 mg L^{-1}) and phosphate (<0.5 $mgPO_4^{3-}\ L^{-1}$) values, the PCQS at Saint Souplet is 'high' and 'good' respectively. However, at the downstream of Cateau-Cambrésis, the PCQS falls to 'moderate' due to the phosphate concentrations (~1.0 $mgPO_4^{3-}\ L^{-1}$). High phosphate concentrations in the surface water are characteristic of urban discharges (Paul and Meyer, 2001). Increases in phosphate loads in rivers, especially during extreme low-flow periods and increases in water temperatures as predicted by Explore 2070 would increase the risk of eutrophication and eventually the degradation of the water quality status (Charlton et al., 2018; van Vliet and Zwolsman, 2008).

During storm events, the surface water quality of the River Selle is degraded, particularly at the upstream of the river. PC 1 describes the variations during storm events since the loading values of river flow increase significantly (Fig. 4b). In comparison to the loading plot of Station 2 (Fig. 4f), the loading values of all the variables at Station 1 (Saint Souplet) are more disturbed. Due to the absence of WWTPs at the upstream of the river, pollution loads from combined sewer overflows (CSOs) discharges and/or leaching of agricultural soils most likely contribute to the increases in turbidity, TOC and phosphates and decreases in dissolved oxygen at Saint Souplet. At the downstream of Cateau-Cambrésis, the consequences of storm events on the water quality are clearly highlighted, particularly during the 'heavy' storm event 6. Indeed, during storm events, additional pollution loads of untreated/poorly treated wastewater from WWTPs, combined sewer overflows (CSOs) and urban run-offs most likely contribute to the significant peaks of phosphates and turbidity and to the decrease in dissolved oxygen. The sharp drop in dissolved oxygen during the storm event 6 could have resulted in a one-off anoxic event.

Aside from the multivariate data analysis, the nitrate and conductivity hystereses give further insights on the functioning of the river during storm events. The clockwise hystereses with a negative gradient indicate that both nitrates and conductivity produced dilution curves during the storm events, confirming once again that the River Selle is primarily dominated by groundwater. Given the shape at the beginning of the hysteresis loop for the 'small', 'average' and 'heavy' storm events, two different mechanisms can be proposed: (i) the storm event starts to generate pressure on the groundwater which immediately feeds the river; and (ii) early soil leaching and storm water discharges have similar salt content and nitrate concentrations as in the river. As a result, river flow increases without any change in conductivity or nitrate concentrations (Fig. 3). The second phase of the hysteresis loop consists in the discharge of less enriched storm water which dilutes the salt content and nitrates in the river. The nitrates and conductivity HI_{mid} values are generally similar, except for the 'average' storm event 4 at Station 1 and the 'heavy' storm event 6 at Station 2 (Table 3). The significantly higher HI_{mid} values for the nitrates suggest that no significant stock of inorganic N is rapidly mobilised from the catchment during 'average' and 'heavy' storm events, as observed for the phosphates where sharp increases occur quite instantaneously after storm events. The comparison of the HI_{mid} values between Station 1 and 2 would have given a better understanding of the behaviour of the nitrates and conductivity. Unfortunately, due to numerous complex hystereses and lack of data for 2 'small' storm events at Station 1, it is difficult to make a robust comparison. Nevertheless, the available HI_{mid} values at Station 1 seem to be more important than at Station 2, suggesting that the dilution mechanism could be more significant at the upstream of the river. The input of a greater volume of storm water less enriched in nitrates could explain the differences in the dilution proportions. A larger volume of storm water with higher phosphate concentrations can also explain why the degradation of the water quality at Saint Souplet is more important compared to the downstream of Cateau-Cambrésis. Indeed, the PCQS according to the phosphates at Saint Souplet decline from 'good' during dry weather to 'moderate' during storm events due to a difference of 1.06 $mgPO_4^{3-}\ L^{-1}$. At the downstream of Cateau-Cambrésis, the PCQS changes from 'moderate' to 'poor' due to a difference of only 0.47 $mgPO_4^{3-}\ L^{-1}$. Phosphates will therefore be limiting for the achievement of the 'good' PCQS imposed by the WFD, particularly at the downstream of the river and sewage systems in the catchment need to be revised. Adaptation and mitigation strategies such as the implementation of retention basins at the upstream of the river could help limiting the impact of climate change on the River Selle.

5. Conclusions

The 4-month high-frequency monitoring of the River Selle at sub-hourly intervals allowed a better understanding of the functioning of the river during spring and summer. The behaviour of key parameters of water quality and nutrients during dry weather and storm events provided the following highlights:

- The behaviour of river flow, water temperature and nitrate concentrations showed that the River Selle is dominated by groundwater. The dilution of the nitrates during storm events clearly shows that the nitrates in the River Selle are provided by the groundwater.
- The decrease in groundwater recharge as predicted by the Explore 2070 project would highly impact the water demand in the catchment and would lead to a decrease in the flow of the River Selle. Due to the reduction in flushing rates, the retention and concentration of pollutants such as phosphates from sewage systems would increase during extreme low flows if wastewater treatment plants are not improved and if sewer systems are not seriously revised.
- The reference station located at Saint Souplet reveals low anthropogenic pressure during dry weather but is significantly impacted during storm events, particularly by phosphates which degrade the PCQS of the river. The changes in the PCQS of the river between dry weather and storm events were easily recorded by the high-frequency monitoring stations but would have been more complicated with a low-frequency monitoring such as grab sampling.
- During dry weather, the River Selle at the downstream of the Cateau-Cambrésis town is severely impacted by phosphates, indicating inputs of poorly treated wastewater into the river. Additional loads of pollution contribute to the degradation of the water quality during storm events as clearly proven by the high-frequency monitoring. In addition, the rise in water temperatures as predicted by the Explore 2070 project could increase the risk of eutrophication.

The Explore 2070 climatic models forecasted relatively constant rainfall for northern France, but longer periods of low flows during summer and more intense rainfall in winter. According to our results, the water quality of the River Selle should deteriorate during spring and summer if measures to reduce dry-weather and storm events pollution sources are not undertaken rapidly. Efforts to combat soil leaching and the revision of sewage works in the catchment of the River Selle are two major points to consider. This study finally revealed the importance of understanding the current behaviour of a water body towards dry weather and storm events before suggesting generalised local scenarios of the impact of climate change on surface water quality. High-frequency monitoring provides good insights but to go further in our predictions, a long-term high-frequency monitoring over at least one year should be performed in order to assess the seasonal dynamics of surface water quality. Results from our study therefore need to be strengthened by an additional high-frequency monitoring in the autumn and winter seasons. However, since long-term high-frequency

monitoring requires important human and financial resources, there is a growing need to develop more cost-effective high-frequency monitoring systems. The on-line high-frequency monitoring of other key parameters such as trace metals, pesticides, pharmaceutical residues and composition of dissolved organic matter also need to be developed to complete our study.

Finally, this paper can be considered as a preliminary work for a scientific strategy which can be implemented by other watersheds in order to better understand the functioning of water bodies according to different weather conditions and by using a high-frequency monitoring. Several key points must be considered: (i) the determination of a reference station and the groundwater composition; (ii) a high-frequency monitoring over at least one year; (iii) the monitoring of pollution tracers to clearly distinguish between the different sources of pollution; and (iv) multivariate data analysis to highlight trends and correlations that cannot be detected by expert eyes. The next important step will be to use the high-frequency data to build an impact model for the prediction of the evolution of water quality under climate change. For a robust model, progress in wastewater treatment technologies, changes in agricultural practices, land-use, population, water demand, global and local environmental policies as well as changes in management strategies must be taken into consideration.

Acknowledgments

This work was supported by the CPER Climibio, the Artois-Picardy Water Agency (APWA), the Hauts-de-France Region, the French Ministry of Higher Education and Research and the European Regional Development. The authors are grateful to David Dumoulin, Melinda George, Veronique Alaimo and Christine Grare from the LASIR (University of Lille) and Giovanni Lamonica from the APWA for their help in the preparation of the field campaigns and analyses.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.246.

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